


# Comparison of Environmental Risk Indices Related to Pesticide Spray Drift in Extensive Agriculture in Uruguay

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## Abstract

Pesticide spray drift is an off-target pathway in extensive cropping systems that can lead to the exposure of non-target organisms and nearby human populations. This study compared drift-related risk indices for pesticides commonly used in Uruguay using two indicator-based methodologies: POCER (terrestrial organisms and human health) and HAIR (aquatic organisms). Risk indices were calculated using locally derived drift deposition percentages measured at 5, 15, 30, 50, 75, and 100 m downwind under a conservative operational scenario (boom height 120 cm; mean wind speed 20 km h<sup>-1</sup>) over residue-covered soil. Risk patterns varied according to active ingredient, droplet size, and distance. For bees, chlorpyrifos exceeded the risk threshold (RI ≥ 1) at all distances, while lambda-cyhalothrin exceeded this threshold with fine and medium droplets but not with very coarse droplets. Earthworm risk indices remained below the threshold (RI < 1) at 5 m for all active ingredients. For aquatic organisms, pyraclostrobin and several insecticides exceeded RI ≥ 1 at 15 m, and the use of coarser droplets reduced but did not always eliminate risk. For human health, most substances showed RI < 1 for bystanders and children, whereas paraquat required larger buffer distances under fine and medium droplets. Overall, the results support the use of scenario-based risk indices as comparative tools and suggest that fixed buffer distances may be insufficient for some active ingredients. Product-specific buffer zones and complementary drift mitigation practices should be considered.

**Keywords:** risk assessment, pesticide drift, safety zones, non-target organisms

## Comparación de índices de riesgo considerando la deriva de productos fitosanitarios en la producción agrícola extensiva del Uruguay

### Resumen

La deriva de pulverización de pesticidas constituye una vía relevante de dispersión fuera del blanco en sistemas agrícolas extensivos, pudiendo generar exposición de organismos no objetivo y de poblaciones humanas cercanas. El presente estudio comparó índices de riesgo asociados a la deriva para pesticidas de uso frecuente en Uruguay mediante dos metodologías basadas en indicadores: POCER (organismos terrestres y salud humana) y HAIR (organismos acuáticos). Los índices se calcularon a partir de porcentajes de deposición por deriva obtenidos localmente, medidos a 5, 15, 30, 50, 75 y 100 m a sotavento, bajo un escenario operativo conservador (altura de botalón de 120 cm y velocidad media del viento de 20 km h<sup>-1</sup>) sobre suelo cubierto con rastrojo. Los resultados mostraron que el riesgo dependió del principio activo, el tamaño de gota y la distancia. En abejas, clorpirifos superó el umbral de riesgo ( $RI \geq 1$ ) en todas las distancias evaluadas, mientras que lambda-cialotrina lo superó con gotas finas y medias. En lombrices, los índices se mantuvieron por debajo del umbral a 5 m. En organismos acuáticos, piraclostrobina y varios insecticidas superaron  $RI \geq 1$  a 15 m, observándose una reducción del riesgo con gotas más gruesas. En salud humana, la mayoría de las sustancias presentó bajo riesgo, aunque paraquat requirió mayores distancias de amortiguamiento bajo gotas finas y medias. En conjunto, los resultados destacan la utilidad de los índices de riesgo como herramientas comparativas y la necesidad de estrategias de mitigación específicas por producto.

**Palabras clave:** evaluación de riesgo, deriva de fitosanitarios, zonas de seguridad, organismos no blanco

## Comparação de índices de risco considerando a utilização de produtos fitossanitários na produção agrícola extensiva no Uruguai

### Resumo

A deriva de pulverização de pesticidas constitui uma via relevante de dispersão fora do alvo em sistemas agrícolas extensivos, podendo resultar na exposição de organismos não alvo e de populações humanas próximas. Este estudo comparou índices de risco associados à deriva para pesticidas amplamente utilizados no Uruguai, utilizando duas metodologias baseadas em indicadores: POCER (organismos terrestres e saúde humana) e HAIR (organismos aquáticos). Os índices foram calculados a partir de percentuais de deposição por deriva obtidos localmente, medidos a 5, 15, 30, 50, 75 e 100 m a sotavento, sob um cenário operacional conservador (altura da barra de pulverização de 120 cm e velocidade média do vento de 20 km h<sup>-1</sup>) em solo coberto por resíduos culturais. Os resultados indicaram que o risco variou conforme o ingrediente ativo, o tamanho de gota e a distância. Para abelhas, o clorpirifós excedeu o limiar de risco ( $RI \geq 1$ ) em todas as distâncias avaliadas, enquanto a lambda-cialotrina o excedeu sob gotas finas e médias. Para minhocas, os índices permaneceram abaixo do limiar a 5 m. Em organismos aquáticos, a piraclostrobina e diversos inseticidas superaram  $RI \geq 1$  a 15 m, com redução do risco ao utilizar gotas mais grossas. Para a saúde humana, a maioria das substâncias apresentou baixo risco, embora o paraquat tenha exigido maiores distâncias de amortecimento em determinadas condições. De modo geral, os resultados reforçam a utilidade dos índices de risco como ferramentas comparativas e a necessidade de medidas de mitigação específicas por produto.

**Palavras-chave:** avaliação de risco, deriva de fitosanitarios, zonas de segurança, organismos não-alvo

## 1. Introduction

Environmental issues have gained increasing relevance in international discussions, driven by social and historical transformations that have redefined global priorities. Since the 1960s, the modern environmental crisis has reshaped production, consumption, and resource management patterns, highlighting the limitations of traditional economic models and the need to balance sustainability with economic development to ensure present and future well-being (Forlani, 2021).

Since the 19<sup>th</sup> century, pesticides have been used to improve agricultural yields. However, it was only after World War II that their use intensified systematically in response to the global need to increase food production during economic recovery (Fundación Solón, 2021; Perobelli, 2025). This intensification peaked during the Green Revolution, when technological packages combining agrochemicals, improved varieties, and intensive agricultural practices were promoted. This transformation redefined production systems in many regions of the world, including Latin America (Evenson & Gollin, 2003; Pingali, 2012).

The rapid adoption of these models in Latin America responded to the urgency of modernizing agriculture to meet both domestic demand and export requirements. The increasing reliance on chemical inputs associated with the expansion of intensive commercial crops such as soybean (*Glycine max*) and maize (*Zea mays*) has been linked to well-documented environmental impacts, including contamination of surface and groundwater and the widespread selection of herbicide-resistant weed populations (Altieri & Nicholls, 2004). The environmental impacts of pesticides have been widely documented, particularly in relation to soil degradation and water quality deterioration under intensive agricultural systems (Muñoz-Morales, et al., 2024). These processes have also been associated with biodiversity loss and reduced ecosystem resilience, potentially compromising the sustainability of production systems (Reiche & Carls, 1996).

In this context, pesticide spray drift is recognized as one of the main pathways of environmental contamination associated with pesticide applications (Jong et al., 2008). Spray drift involves the unintended transport of droplets outside the target area, reducing application efficiency and increasing the risk of exposure for non-target organisms and human populations (Heidary et al., 2014). Application technologies such as nozzle selection and droplet size have been identified as key factors influencing spray drift, with coarser droplets significantly reducing off-target deposition (Bueno et al., 2017; Chethan et al., 2019).

Experimental evidence under local conditions indicates that adequate biological efficacy can be achieved using coarse droplets. Studies have shown effective control with fungicides (Olivet et al., 2017), insecticides (Olivet et al., 2013), and contact herbicides such as paraquat (Balbuena et al., 2018). At the same time, the use of coarser droplets has been consistently associated with reduced spray drift (Bueno et al., 2016). However, despite this evidence, the adoption of drift-reducing technologies remains limited in Uruguay (Bentancur, 2017).

The quantification of spray drift is essential for the development of risk assessment tools. Risk indices provide a framework to estimate potential impacts on environmental compartments and human health under defined exposure scenarios.

The POCER (Pesticide Occupational and Environmental Risk) methodology evaluates pesticide-related risks by integrating exposure and toxicity for multiple receptors, including aquatic organisms, terrestrial organisms, and human populations (Vercruyse & Steurbaut, 2002).

The HAIR (Harmonised Environmental Indicators for Pesticide Risk) methodology provides a harmonized framework for assessing pesticide risks in Europe, incorporating updated toxicological data and standardized exposure scenarios (Kruijne et al., 2011).

Both approaches support the definition of mitigation strategies such as buffer zones, which aim to reduce the exposure of sensitive environments to spray drift. In these frameworks, risk indices are commonly interpreted using threshold values, where  $RI \geq 1$  indicates a level of concern (Ramos et al., 2000).

In Uruguay, regulatory frameworks establish minimum buffer distances and operational requirements to reduce pesticide exposure. These include restrictions for applications near sensitive areas and water bodies, as well as requirements related to equipment use and applicator training (Dirección General de Servicios Agrícolas, 2008;

Ministerio de Ganadería, Agricultura y Pesca, 2011). In addition, Good Agricultural Practices provide technical recommendations to reduce spray drift, including nozzle selection, calibration, and consideration of meteorological conditions (Alves et al., 2014).

However, the implementation of these practices may vary under real farming conditions, leading to differences between predicted and actual exposure levels. Therefore, risk indices represent comparative tools that allow the evaluation of relative differences among substances, application technologies, and environmental scenarios.

Therefore, the objective of this study was to assess environmental and human health risks associated with pesticide spray drift in extensive cropping systems in Uruguay through the calculation and comparison of different risk indices.

## 2. Materials and Methods

For the calculation of risk indices, the HAIR and POCER methodologies were employed (Kruijne et al., 2011; Vercruyse & Steurbaut, 2002). The experimental spray drift data used corresponded to those reported by Saracho et al. (2025) (Table 1). The highest-risk scenario was selected, defined by a boom height of 120 cm and an average wind speed of 20 km h<sup>-1</sup>.

Spray drift was evaluated under different droplet size categories following the ISO standard FDIS 22866 (International Organization for Standardization, 2005). Applications were carried out over a stubble-covered surface, with no crop growing at the time of application. Therefore, the evaluated scenario represents applications performed on residue-covered soil rather than on green crop canopies, which are common in pre-sowing or post-harvest management practices in extensive agricultural systems.

Risk indices were calculated under the assumption that the applied dose reached the soil surface, without explicitly accounting for potential interception by standing vegetation or crop canopy. Consequently, the calculated indices represent a conservative exposure scenario and may not fully reflect situations where part of the applied product is retained by green cover. In addition, the calculations do not incorporate rainfall-related processes (timing and intensity) that could influence the transfer of active ingredients from plant surfaces or residues to the soil.

Drift measurements were conducted using collectors placed along the wind direction at fixed distances of 5, 15, 30, 50, 75, and 100 m from the application area.

**Table 1.** Average spray drift (%) at different distances and droplet sizes

Droplet size	Distance (meters)					
	5	15	30	50	75	100
Very coarse (350-550 µm)	2.8% Ba	1.8% Bb	1.4% Ab	1.4% Ab	0.7% Ac	0.1% Ac
Medium (250-400 µm)	4.4% Ba	2.2% Bb	1.8% Ab	1.5% Ab	0.8% Ac	0.5% Ac
Fine (250-280 µm)	9.4% Aa	3.9% Ab	2.7% Ab	1.8% Ab	1.5% Ab	0.9% Ac

Values represent mean drift percentages obtained under field conditions during two consecutive growing seasons. Distances correspond to the downwind measurement points (m), and droplet size categories were defined according to nozzle classification. Uppercase letters indicate significant differences among droplet size categories within the same distance, while lowercase letters indicate significant differences among distances within the same droplet size category, according to Tukey's HSD test ( $p < 0.05$ ).

The pesticides selected for the calculation of risk indices included fungicides, herbicides, and insecticides commonly used in extensive cropping systems in Uruguay. The selection was based on a survey conducted among technical advisors, who identified the most frequently used products (Table 2). All selected products were verified to be registered on the official website of the Ministry of Livestock, Agriculture and Fisheries.

Toxicological and ecotoxicological information for each active ingredient was retrieved from the Pesticide Properties Database (PPDB) (Agriculture & Environment Research Unit, n.d.). The application rates considered corresponded to those recommended on the label of each commercial product. The selected active ingredients are listed in Table 2, while their toxicological and ecotoxicological characteristics are detailed in the annexes, the data can be found in Table S1 and S2 of the Supplementary material.

**Table 2.** Active ingredients selected within each category of phytosanitary products and their soil adsorption coefficients (Koc) obtained from PPDB

Phytosanitary	Products	Koc (mL g <sup>-1</sup> )
Herbicides	Clethodim	-
Herbicides	2,4-D	39.3
Herbicides	Paraquat	1000000
Herbicides	Pinoxaden	-
Insecticides	Chlorantraniliprole	362
Insecticides	Lambda-cyhalothrin	283707
Insecticides	Chlorpyrifos	5509
Fungicides	Pyraclostrobin	9304
Fungicides	Fluxapyroxad	-
Fungicides	Epoxiconazole	-

Soil adsorption coefficients (Koc) were obtained exclusively from the Pesticide Properties Database (Agriculture & Environment Research Unit, n.d.). A dash (-) indicates that no single representative Koc value was available in PPDB for the corresponding active ingredient.

## 2.1 Risk Assessment Frameworks and Indicators

Risk assessment was conducted using two indicator-based methodologies: the POCER (Pesticide Occupational and Environmental Risk indicator) (Vercruyssen & Steurbaut, 2002) and the HAIR (Harmonised Environmental Indicators for Pesticide Risk) framework (Kruijnen et al., 2011). POCER was used to assess risks for terrestrial non-target organisms and human health, whereas HAIR was applied to evaluate risks for aquatic organisms associated with spray drift.

### 2.1.1 Risk Assessment Using the POCER Methodology

The POCER indicator is a modular approach designed to evaluate occupational and environmental risks of pesticides under standardized exposure scenarios (Vercruyssen & Steurbaut, 2002).

## Terrestrial Non-Target Organisms

### Risk Index for Bees

Risk to bees was assessed using a hazard quotient approach, defined as the ratio between the application rate of the active ingredient and the acute median lethal dose (LD<sub>50</sub>) for bees. Spray drift was considered the relevant exposure pathway. The risk index for bees (RI<sub>bees</sub>) was calculated as:

$$RI_{bees} = \frac{(AR \times (\text{drift\%/100}))}{(LD_{50} \text{ bees})} \times 1000 \quad \text{Equation 1}$$

where *AR* is the application rate (kg AI ha<sup>-1</sup>), *drift%* is the percentage of deposited spray drift at a given distance, and *LD<sub>50</sub> bees* is expressed in µg AI bee<sup>-1</sup>. The factor 1000 converts the application rate from kg to g.

### Risk Index for Earthworms

Risk to earthworms was evaluated based on the predicted environmental concentration in soil (PEC<sub>soil</sub>), assuming that spray drift deposits onto the soil surface. The PEC<sub>soil</sub> was calculated considering a soil depth of 0.05 m (5 cm), corresponding to the surface layer where pesticides with relatively high adsorption coefficients (*K<sub>oc</sub>*) and low mobility are expected to accumulate.

$$PEC_{soil} = \frac{(AR \times d\% \times N \times (1-f))}{(d \times \rho)} \quad \text{Equation 2}$$

where *N* is the number of applications, *f* is the fraction of deposited active ingredient intercepted by the crop canopy, *d* is soil depth (m), and *ρ* is soil bulk density (kg m<sup>-3</sup>).

The earthworm risk index was then calculated as:

$$RI_{earthworms} = \frac{PEC_{soil} \times 10}{LC_{50} \text{ earthworms}} \quad \text{Equation 3}$$

where *LC<sub>50</sub> earthworms* is expressed in mg AI kg<sup>-1</sup> soil. The factor 10 accounts for unit consistency within the POCER framework.

The parameters used for the assessment of risk to terrestrial non-target organisms within the POCER framework are presented in [Table 3](#).

**Table 3.** POCER – Terrestrial non-target organisms

Parameter	Description	Unit	Value
AR	Application rate of active ingredient	kg AI ha <sup>-1</sup>	–
drift%	Percentage of deposited spray drift	%	–
N	Number of applications	–	1
F	Fraction intercepted by crop canopy	–	0
D	Soil depth	m	0.05
P	Soil bulk density	kg m <sup>-3</sup>	–
LD <sub>50</sub> bees	Median lethal dose for bees	µg AI bee <sup>-1</sup>	–
LC <sub>50</sub> earthworms	Median lethal concentration for earthworms	mg AI kg <sup>-1</sup> soil	–

The values presented correspond to input parameters of predictive risk assessment models (POCER), defined based on standardized scenarios and conservative assumptions. These parameters are derived from model default values and/or typical field conditions and are used for comparative purposes to estimate potential risk under defined exposure scenarios, rather than to describe site-specific conditions.

### Human Health Risk Indicators

Human health risk indicators were calculated for three population groups potentially exposed to spray drift: adult bystanders, residents living near treated areas, and children. Exposure pathways considered included dermal contact and inhalation of airborne spray drift, as defined in the POCER methodology. Parameter values were selected according to standardized exposure scenarios and represent conservative but realistic assumptions.

### Risk Index for Bystanders

Adult bystanders were assumed to be present near the treated area for a short duration during or immediately after application. Dermal and inhalation exposure were calculated as follows:

$$\text{ED bystanders} = \text{AR} \times \% \text{drift} \times \text{EA} \quad \text{Equation 4}$$

$$I \text{ bystanders} = \frac{\text{AI} \times \text{AR} \times \text{DED}_{\text{bystanders}}}{\text{st}} \quad \text{Equation 5}$$

Total risk was calculated relative to the acceptable operator exposure level (AOEL):

$$\text{RI}_{\text{bystanders}} = \frac{(\text{DE} \times \text{Ab DE} + I \times \text{AbI})}{\text{BW} \times \text{AOEL}} \quad \text{Equation 6}$$

### Risk Index for Residents

Residents were assumed to experience repeated exposure due to multiple applications over time. A standard downwind distance of 50 m was considered.

$$\text{ED}_{\text{residents}} = \text{AR} \times \% \text{drift} \times \text{FA} \times \text{EA} \times (\text{RD}/365) \quad \text{Equation 7}$$

$$I \text{ residents} = \frac{\text{IAI} \times \text{AR} \times \text{DED}_{\text{residents}}}{\text{st}} \times \text{EF} \times \text{YED} \quad \text{Equation 8}$$

$$\text{RI}_{\text{residents}} = \frac{(\text{DE} \times \text{Ab DE} + I \times \text{AbI})}{\text{BW} \times \text{AOEL}} \quad \text{Equation 9}$$

### Risk Index for Children

Children were considered a particularly sensitive group. Exposure pathways included direct dermal contact with spray drift, dermal contact with contaminated grass, oral exposure through hand-to-mouth or object-to-mouth behavior, and inhalation.

Equations 10-16 (Dermal and oral exposure components):

$$\text{ED}_{\text{children direct}} = \text{AR} \times \% \text{drift} \times \text{EA} \quad \text{Equation 10}$$

$$\text{ED}_{\text{grass}} = 10^{-4} \times \text{AR} \times \% \text{d} \times \text{TTR}_{\text{grass}} \times \text{TF} \times \text{DED} \quad \text{Equation 11}$$

$$\text{ED}_{\text{consumption}} = 10^{-4} \times \text{AR} \times \% \text{d} \times \text{TTR}_{\text{grass}} \times \text{SE} \times \text{EA}_{\text{fingers}} \times \text{N event} \times \text{DED} \quad \text{Equation 12}$$

$$\text{ED}_{\text{object}} = 10^{-4} \times \text{AR} \times \% \text{d} \times \text{TTR}_{\text{object}} \times \text{IgR} \quad \text{Equation 13}$$

$$\text{ED}_{\text{total}} = \text{ED}_{\text{children direct}} + \text{ED}_{\text{grass}} + \text{ED}_{\text{consumption}} + \text{ED}_{\text{object}} \quad \text{Equation 14}$$

Inhalation exposure was calculated as:

$$I = \frac{(\text{Ia} \times \text{AR} + \text{DED})}{\text{ST}} \quad \text{Equation 15}$$

The child risk index was calculated as:

$$RI = \frac{(DE_{total} \times Ab_{DE} + I \times Ab)}{BE_{children} \times AOEL} \quad \text{Equation 16}$$

The parameters considered for the assessment of human health risk, including bystanders, residents, and children, are presented in [Table 4](#).

**Table 4.** Parameters used for POCER human health risk assessment

Parameter	Description	Unit	Value
EA	Exposed body surface area (adult)	m <sup>2</sup>	0.4225
DED bystanders	Exposure duration	min day <sup>-1</sup>	1
ST	Application time per hectare	min ha <sup>-1</sup>	7.69
Ab_DE	Dermal absorption	–	0.1
Ab_I	Inhalation absorption	–	1
BW	Adult body weight	kg	70
AOEL	Acceptable exposure level	mg kg <sup>-1</sup> day <sup>-1</sup>	–
EA children	Exposed surface area (child)	m <sup>2</sup>	0.2
BW children	Child body weight	kg	15
TTR grass	Transfer coefficient (grass)	–	0.05
TF	Transfer factor	cm <sup>2</sup> h <sup>-1</sup>	5200
EF	Exposure frequency	–	0.25
RD	Residential days	days	90

The values presented correspond to input parameters of predictive risk assessment models (POCER), defined based on standardized scenarios and conservative assumptions. These parameters are derived from model default values and/or typical field conditions and are used for comparative purposes to estimate potential risk under defined exposure scenarios, rather than to describe site-specific conditions.

## 2.2 Risk Assessment Using the HAIR Methodology

The HAIR framework was applied exclusively to assess risks for aquatic non-target organisms associated with spray drift. HAIR uses standardized environmental exposure scenarios to ensure harmonized risk assessment and comparability among active ingredients.

### Aquatic Non-Target Organisms

Aquatic exposure was estimated assuming deposition of spray drift into a standardized field ditch. All evaluated distances were considered; however, particular emphasis was placed on the 15 m downwind distance, which is consistent with Uruguayan regulations for ground applications.

The predicted environmental concentration in water was calculated as:

$$PEC_{aquatic\ organisms} = \frac{(AR \times d\%) \times n}{d_{ditch} \times 1000} \quad \text{Equation 17}$$

The 1000 factor is a unit-conversion factor.

where  $D_{ditch}$  is ditch depth (m), and the factor 1000 ensures unit consistency.

Toxicity reference values were defined for fish, daphnia, and algae:

Equations 18-20:

$$\text{Fish} = \frac{\text{LC}_{50} \text{ fish}}{100} \quad \text{Equation 18}$$

$$\text{Daphnia} = \frac{\text{CE}_{50} \text{ daphnia}}{100} \quad \text{Equation 19}$$

$$\text{Algae} = \frac{\text{NOEC algae}}{10} \quad \text{Equation 20}$$

The aquatic risk index was calculated using the most sensitive endpoint:

$$\text{RI aquatic organisms} = \frac{\text{PEC AO}}{\min(\text{NORM AO})} \quad \text{Equation 21}$$

The parameters used for the assessment of risk to aquatic organisms within the HAIR framework are presented in [Table 5](#).

**Table 5.** HAIR – Aquatic organisms

Parameter	Description	Unit	Value
AR	Application rate of active ingredient	kg AI ha <sup>-1</sup>	–
drift%	Percentage of deposited spray drift	%	–
N	Number of applications	–	1
D_ditch	Ditch depth	M	0.5
LC <sub>50</sub> fish	Median lethal concentration for fish	mg L <sup>-1</sup>	–
EC <sub>50</sub> daphnia	Median effect concentration for daphnia	mg L <sup>-1</sup>	–
NOEC algae	No observed effect concentration for algae	mg L <sup>-1</sup>	–

The values presented correspond to input parameters of predictive risk assessment models (HAIR), defined based on standardized scenarios and conservative assumptions. These parameters are derived from model default values and/or typical field conditions and are used for comparative purposes to estimate potential risk under defined exposure scenarios, rather than to describe site-specific conditions.

### 2.3 Determination of Buffer Zone Width

Based on the calculated risk indices, minimum buffer zone widths were determined for each active ingredient. Buffer distances were increased incrementally until the corresponding risk index fell below one (RI < 1). The distance at which this threshold was reached was defined as the minimum buffer zone required to mitigate spray drift-related risks under the evaluated scenarios.

The scenarios and risk indices applied in this study are primarily intended as illustrative and comparative tools, used to evaluate relative differences in spray drift-related risk under defined and standardized conditions. Rather than providing precise predictions for all possible field situations, the indices allow comparison among substances, droplet sizes, and distances, supporting the interpretation of potential risk trends and the relative effectiveness of mitigation measures such as buffer zones. Consequently, the results should be interpreted within the context of the selected scenarios and assumptions, acknowledging that actual field conditions may vary.

For transparency and interpretation purposes, risk indices calculated using both POCER and HAIR frameworks are dimensionless indicators designed to express relative risk under standardized exposure scenarios. In both methodologies, index values typically range from values close to zero, indicating negligible risk, to values equal to or greater than 1, which indicate a potential level of concern. An index value below 1 (RI < 1) is generally interpreted as an acceptable or low risk, whereas values equal to or exceeding 1 (RI ≥ 1) indicate a potential

risk requiring attention or mitigation. Therefore, the indices are primarily intended for comparative assessment across scenarios, substances, and application conditions, rather than for absolute risk quantification.

### 3. Results

#### 3.1 Risk Indicators for Non-Target Organisms

##### 3.1.1 Terrestrial Organisms (Bees and Earthworms)

Table 6 shows that the minimum safe distance to protect bees from pesticide drift varied according to the active ingredient and droplet size. Chlorpyrifos exhibited the highest risk index (RI) values, exceeding the safety threshold (RI < 1) under all evaluated conditions. Lambda-cyhalothrin also exceeded the threshold with fine (RI = 1.9) and medium droplets (RI = 1.0), while RI values decreased below 1 with very coarse droplets. Among fungicides and herbicides, none exceeded RI = 1 except paraquat, where the risk level depended on droplet size.

**Table 6.** Relationship between risk index and safe distances for bees according to droplet size

Phytosanitary product	Active ingredient	Droplet size					
		Fine droplet		Medium droplet		Very coarse droplet	
		RI	Safe distance (m)	RI	Safe distance (m)	RI	Safe distance (m)
Fungicide	Pyraclostrobin	0.1	5	0.0	5	0.0	5
Fungicide	Fluxapyroxad	0.1	5	0.1	5	0.0	5
Fungicide	Epoxiconazole	0.1	5	0.1	5	0.0	5
Herbicide	Pinoxaden	0.0	5	0.0	5	0.0	5
Herbicide	2,4-D	0.5	15	0.6	5	0.4	5
Herbicide	Clethodim	0.1	5	0.0	5	0.0	5
Herbicide	Paraquat	0.3	100	0.6	75	0.5	75
Insecticide	Chlorantraniliprole	0.6	15	0.7	5	0.4	5
Insecticide	Lambda-cyhalothrin	1.9	>100	1	>100	0.2	100
Insecticide	Chlorpyrifos	66.3	>100	35.4	>100	7.2	>100

Safe distance for bees considering a risk index lower than 1.

For earthworms, the results indicated that, regardless of droplet size category and active ingredient, no RI ≥ 1 was observed at the minimum evaluated distance (5 m) (Table 7).

**Table 7.** Risk index (RI) for earthworms at 5 m from the field edge under different droplet size categories

Active ingredient	Fine droplet	Medium droplet	Very coarse droplet
	RI	RI	RI
Pyraclostrobin	0.0003	0.0001	0.0001
Fluxapyroxad	0.0001	0.0000	0.0000
Epoxiconazole	0.0004	0.0002	0.0001
Pinoxaden	0.0001	0.0001	0.0000
Clethodim	0.0049	0.0023	0.0014
2,4-D	0.0094	0.0044	0.0028
Paraquat	0.0011	0.0005	0.0003
Chlorantraniliprole	0.0001	0.0000	0.0000
Lambda-cyhalothrin	0.0000	0.0000	0.0000
Chlorpyrifos	0.0056	0.0026	0.0016

Risk indices (RI) were calculated for earthworms based on pesticide spray drift at a fixed distance of 5 m from the field edge. Droplet size categories were defined according to nozzle classification.

### 3.1.2 Aquatic Organisms

The RI values for aquatic organisms varied according to the active ingredient and droplet size (Table 8). Among fungicides, pyraclostrobin showed the highest risk, exceeding  $RI = 1$ . Herbicides did not reach  $RI \geq 1$  at 15 m. In insecticides, chlorantraniliprole reached  $RI \geq 1$  with fine and medium droplets, but not with coarse droplets. Lambda-cyhalothrin and chlorpyrifos exceeded  $RI = 1$  at all droplet sizes, with chlorpyrifos showing particularly high values.

**Table 8.** Risk index at 15 m for aquatic organisms, determined by pesticide drift

Active ingredient	Droplet size		
	Fine droplet	Medium droplet	Very coarse droplet
	RI	RI	RI
Pyraclostrobin	5.7	3.3	2.6
Fluxapyroxad	0.1	0.1	0.1
Epoxiconazole	0.6	0.4	0.3
Pinoxaden	0.0	0.0	0.0
2,4-D	0.0	0.0	0.0
Clethodim	0.0	0.0	0.0
Paraquat	0.1	0.0	0.0
Chlorantraniliprole	2.0	1.2	0.9
Lambda-cyhalothrin	12.7	7.3	5.8
Chlorpyrifos	1875	1077.2	846.9

## 3.2 Human Health Risk Indicators

### 3.2.1 Bystanders

Fungicides presented  $RI < 1$  at all droplet sizes and distances (Table 9). Among herbicides, paraquat exceeded  $RI = 1$  at most droplet sizes, requiring buffer zones  $> 100$  m with fine droplets and 100 m with medium droplets. Insecticides showed  $RI < 1$  under all conditions, although chlorpyrifos presented higher RI values compared to the other active ingredients.

**Table 9.** Risk index and safe distance for bystanders according to droplet size

Active ingredient	Droplet size					
	Fine droplet		Medium droplet		Very coarse droplet	
	RI	Safe distance* (m)	RI	Safe distance* (m)	RI	Safe distance* (m)
Pyraclostrobin	0.1	5	0.0	5	0.0	5
Fluxapyroxad	0.0	5	0.0	5	0.0	5
Epoxiconazole	0.1	5	0.0	5	0.0	5
Pinoxaden	0.0	5	0.0	5	0.0	5
2,4-D	0.2	15	0.2	5	0.1	5
Clethodim	0.1	5	0.0	5	0.0	5
Paraquat	1.2	>100	0.6	100	0.8	75
Chlorantraniliprole	0.0	5	0.0	5	0.0	5
Lambda-cyhalothrin	0.1	5	0.0	5	0.0	5
Chlorpyrifos	0.3	5	0.1	5	0.1	5

\*Safe distance for bystanders considering a risk index lower than 1.

### 3.2.2 Residents

For residents, RI values remained well below the threshold of concern ( $RI < 1$ ) across all active ingredients and droplet size categories (Table 10).

**Table 10.** Risk index (RI) for residents at a fixed distance of 50 m under different droplet size categories

Active ingredient	Droplet size		
	Fine droplet	Medium droplet	Very coarse droplet
Pyraclostrobin	0.0	0.0	0.0
Fluxapyroxad	0.0	0.0	0.0
Epoxiconazole	0.0	0.0	0.0
Pinoxaden	0.0	0.0	0.0
2,4-D	0.0	0.0	0.0
Clethodim	0.0	0.0	0.0
Paraquat	0.1	0.1	0.1
Chlorantraniliprole	0.0	0.0	0.0
Lambda-cyhalothrin	0.0	0.0	0.0
Chlorpyrifos	0.0	0.0	0.0

Safe distance for children considering a risk index lower than 1.

### 3.2.3 Children

For children, RI values were below the threshold of concern ( $RI < 1$ ) for most active ingredients at a minimum distance of 5 m across droplet size categories (Table 11). In contrast, paraquat exhibited substantially higher RI values under fine and medium droplet scenarios, requiring safety distances greater than 100 m to achieve  $RI < 1$ , while the use of very coarse droplets reduced RI values below the threshold.

**Table 11.** Risk index (RI) and safe distance for children under different droplet size categories

Active ingredient	Droplet size					
	Fine droplet		Medium droplet		Very coarse droplet	
	RI	Safe distance* (m)	RI	Safe distance* (m)	RI	Safe distance* (m)
Pyraclostrobin	0.0	5	0.0	5	0.0	5
Fluxapyroxad	0.0	5	0.0	5	0.0	5
Epoxiconazole	0.0	5	0.0	5	0.0	5
Pinoxaden	0.0	5	0.0	5	0.0	5
2,4-D	0.4	5	0.3	5	0.3	5
Clethodim	0.0	5	0.0	5	0.0	5
Paraquat	3.5	>100	3.5	>100	0.9	100
Chlorantraniliprole	0.0	5	0.0	5	0.0	5
Lambda-cyhalothrin	0.0	5	0.0	5	0.0	5
Chlorpyrifos	0.3	5	0.1	5	0.1	5

\*RI values were calculated for children based on pesticide spray drift. Safe distance corresponds to the minimum distance required to achieve a risk index lower than 1.

## 4. Discussion

The results demonstrated that the risk associated with pesticide spray drift varied markedly according to the organism assessed, the active ingredient, and application-related factors, specifically droplet size and distance from the field edge. These findings allow the identification of differentiated vulnerability patterns and provide relevant evidence to support the refinement of buffer zones and the implementation of mitigation measures.

## 4.1 Risk to Terrestrial Organisms

Bees are particularly sensitive to pesticide drift due to their ecological role in pollination and their frequent presence in both agricultural and non-agricultural landscapes (Alabama A&M University & Auburn University, 1998). Risk index (RI) values showed that chlorpyrifos represented the highest hazard, exceeding the safety threshold ( $RI < 1$ ) under all evaluated conditions. This result is consistent with previous studies that have documented negative effects of insecticides on pollinator health, including increased mortality and sublethal impacts affecting colony dynamics (Shaher & Manjy, 2020).

Although national regulations restrict pesticide applications during flowering periods, exposure may still occur through spray drift affecting spontaneous vegetation at field margins, which can attract pollinators even in the absence of direct application.

The insecticide lambda-cyhalothrin, despite its high intrinsic toxicity, showed lower RI values due to reduced application rates. However, RI values exceeded the threshold under fine and medium droplet conditions, highlighting the importance of droplet size as a key factor influencing drift-related risk. In contrast, most fungicides and herbicides showed low RI values, with the exception of paraquat, which exhibited higher risk levels associated with its intrinsic toxicity.

It is important to note that the RI approach is based on acute toxicity endpoints and does not account for sublethal or chronic effects. Previous studies have reported behavioral alterations, reduced reproduction, and long-term colony effects associated with pesticide exposure (Riaño-Jimenez & Cure, 2016; Shaher & Manjy, 2020). These limitations highlight the need to complement risk assessment approaches with studies addressing chronic exposure scenarios.

For earthworms, RI values remained below the threshold under all evaluated conditions, which is consistent with studies indicating that acute toxicity is generally low under field-realistic exposure scenarios. However, repeated pesticide applications may lead to cumulative effects and increased long-term exposure in soils (Edwards & Bohlen, 1996; Pelosi et al., 2014).

## 4.2 Risk to Aquatic Organisms

Risk index (RI) values for aquatic organisms at 15 m varied markedly among active ingredients and droplet size categories (Table 8), indicating substantial differences in drift-related aquatic risk under standardized exposure conditions. These differences reflect the combined influence of intrinsic aquatic toxicity, application rate, drift deposition, and compound-specific environmental behavior, including soil adsorption potential.

Among fungicides, pyraclostrobin exhibited the highest RI values, exceeding the threshold of concern ( $RI \geq 1$ ) under all droplet size categories. This response was primarily driven by its high toxicity to aquatic organisms, particularly fish and algae. Although pyraclostrobin presents a relatively high soil adsorption coefficient ( $K_{oc} = 9,304 \text{ mL g}^{-1}$ ), aquatic exposure in the evaluated scenario resulted from direct spray drift deposition into a standardized field ditch. Under these conditions, toxicity dominated the risk index, and reductions in drift achieved through coarser droplets were insufficient to lower RI values below the threshold. In contrast, fluxapyroxad and epoxiconazole showed substantially lower RI values. For epoxiconazole, RI decreased consistently with increasing droplet size, indicating that drift-reduction measures were more effective for compounds with lower aquatic toxicity.

Herbicides did not reach  $RI \geq 1$  at 15 m for any droplet size category. Paraquat showed low RI values despite its high intrinsic toxicity, which can be partly explained by its extremely high soil adsorption coefficient ( $K_{oc} = 1,000,000 \text{ mL g}^{-1}$ ). This strong affinity for soil particles limits its persistence in the water phase and reduces

effective aquatic exposure following drift deposition. These results highlight that aquatic risk is not solely determined by toxicity, but is strongly modulated by partitioning behavior and dilution capacity within aquatic compartments.

Insecticides represented the highest level of concern for aquatic organisms. Chlorantraniliprole reached or exceeded the RI threshold with fine and medium droplets but fell below  $RI = 1$  when very coarse droplets were applied. This behavior is consistent with its intermediate aquatic toxicity and moderate soil adsorption ( $K_{oc} = 362 \text{ mL g}^{-1}$ ), making its risk sensitive to reductions in drift deposition. In contrast, lambda-cyhalothrin and chlorpyrifos exceeded  $RI = 1$  across all droplet size categories. For lambda-cyhalothrin, extremely high aquatic toxicity outweighed its strong soil adsorption, while chlorpyrifos showed very high RI values driven by its intrinsic toxicity. These results are consistent with previous studies highlighting the high sensitivity of aquatic organisms to insecticides and the importance of spray drift as a pathway of contamination (Bueno, 2015; Eaton et al., 2008).

These results are particularly relevant in the context of Uruguayan regulations, which establish a minimum buffer distance of 10 m between terrestrial applications and surface water bodies. The persistence of  $RI \geq 1$  at 15 m for several insecticides indicates that a uniform buffer distance may be insufficient to protect aquatic ecosystems from spray drift for highly toxic compounds.

### 4.3 Risk to Human Health

Estimated human health risk varied among exposure groups, active ingredients, and application scenarios, reflecting differences in both toxicological properties and modeled exposure pathways. For bystanders, most fungicides and insecticides were associated with RI values below the threshold of concern under the evaluated conditions. In contrast, paraquat showed higher RI values under fine and, to a lesser extent, medium droplet scenarios, in some cases exceeding  $RI = 1$ . This pattern may be related to its high intrinsic toxicity and acute hazard classification by the World Health Organization (WHO), which categorizes paraquat as class Ib (highly hazardous), particularly when inhalation or dermal exposure occurs (Wesseling et al., 2001).

The herbicide 2,4-D showed intermediate RI values that varied with droplet size, suggesting that application characteristics may influence estimated exposure levels. Chlorpyrifos, although remaining below the threshold in the assessed scenarios, presented comparatively higher RI values than other insecticides. This observation may be relevant given previous evidence linking chlorpyrifos exposure to neurodevelopmental effects in sensitive populations, including children and pregnant women, as reported in epidemiological and toxicological studies (Lee et al., 2016).

For residents, RI values were consistently close to zero across all active ingredients and droplet size categories at a distance of 50 m. This outcome reflects the standardized exposure assumptions applied in the assessment, where residents are exposed primarily to diluted off-target drift at greater distances from the treated area. Therefore, low RI values should be interpreted within the context of these assumptions rather than as evidence of absence of drift or exposure.

Children tended to show higher estimated RI values than adults, likely due to lower body weight and the inclusion of additional exposure pathways in the model, such as dermal contact with contaminated surfaces and incidental ingestion. Similar considerations regarding children's vulnerability to pesticide exposure through dermal and inhalation pathways have been highlighted in previous studies (Bueno, 2015).

Overall, these findings indicate that human health risk associated with spray drift is influenced by the interaction between active ingredient toxicity, application technology, and exposure assumptions. Consequently, risk indices should be interpreted as comparative indicators under defined scenarios, rather than as definitive measures of safety or hazard.

#### 4.4 Study Limitations and Recommendations

Assessing the environmental and human health impacts of phytosanitary products is a complex and multidimensional challenge, involving multiple exposure pathways, biological responses, and spatial and temporal scales. Within this broad context, the present study provides a focused contribution by addressing risks associated specifically with pesticide spray drift, while acknowledging that this represents only one component of overall environmental exposure.

Accordingly, the assessment did not consider other relevant contamination pathways such as surface runoff and erosion, which have been widely recognized as important sources of pesticide transport to aquatic and terrestrial ecosystems (Jong et al., 2008). Nor did it address sublethal or chronic effects on non-target organisms, or interactions arising from pesticide mixtures, which are common under agricultural conditions and may enhance toxic responses (Shaher & Manjy, 2020).

In addition, differences in the environmental fate of pesticides were not explicitly incorporated into the analysis. Active ingredients vary substantially in their degradation rates, mobility, and transformation processes, and some compounds may rapidly form metabolites with distinct toxicological profiles compared to the parent substance. These processes can influence long-term exposure and risk, particularly in soils and surface waters, and represent an additional source of uncertainty when interpreting risk indices derived from short-term exposure scenarios.

The risk indices applied in this study were calculated using established modeling approaches and standardized parameter values, which are widely used to ensure comparability among active ingredients, droplet size categories, and exposure groups. While this approach is appropriate for relative risk screening and scenario comparison, it does not fully capture site-specific variability related to environmental conditions or management practices.

Future research would therefore benefit from integrating multiple exposure pathways, incorporating environmental fate processes and chronic toxicity endpoints, and refining model parameterization through long-term field studies. Such efforts are essential to advance a more comprehensive understanding of pesticide-related risks and to support the development of effective mitigation strategies and regulatory frameworks.

#### 5. Conclusions

The comparative risk analysis associated with pesticide drift in extensive production systems enabled the identification of different vulnerability patterns among organisms and human groups. The results showed that sensitivity varies not only by the group evaluated, but also depending on the active ingredient and the application technology used.

These findings reinforce the need to define buffer zones specifically for each pesticide, taking into account differences in toxicity and drift-related behavior, rather than applying generalized criteria across active ingredients. In particular, compounds such as chlorpyrifos, lambda-cyhalothrin, and paraquat require special attention due to their high toxicity, even when drift-reducing technologies are adopted.

The study also highlights the usefulness of complementary risk assessment tools such as POCER and HAIR for supporting decision-making in environmental management and human health protection. While these methodologies rely on different exposure scenarios and calculation approaches, their combined application allowed a more comprehensive evaluation of drift-related risks across multiple organism groups.

However, the application of such tools should be complemented by assessments that incorporate sublethal, cumulative, and mixture effects, which are increasingly common under current pesticide application schemes.

Overall, the results underscore the importance of promoting public policies and technical training programs that encourage the adoption of safer application technologies and regulatory approaches differentiated by active ingredient. Such measures may contribute to advancing agricultural systems that are more compatible with the protection of human health and the environment.

### Transparency of Data

Data not available: The data set that supports the results of this study is not publicly available.

### Author Contribution Statement

	W Saracho	I García	JPAR da Cunha	J Villalba
Conceptualization				
Data curation				
Formal analysis				
Investigation				
Methodology				
Project administration				
Resources				
Supervision				
Validation				
Visualization				
Writing – original draft				
Writing – review and editing				

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## Supplementary Material

**Table S1.** Characteristics of the selected commercial products

Commercial product	Active ingredient	Active ingredient concentration (g L <sup>-1</sup> )	Application rate (kg a.i. ha <sup>-1</sup> )
Priax	Pyraclostrobin	333.0	0.117
Priaxor	Fluxapyroxad	167.0	0.058
Alezate	Epoxiconazole	125.0	0.125
Pinoxaden	Pinoxaden	50.0	0.040
2,4-D	2,4-D	760.0	1.140
Cletomax	Clethodim	240.0	0.168
Paraquat	Paraquat	200.0	0.700
Coragen	Chlorantraniliprole	200.0	0.060
Zero 50 EC	Lambda-cyhalothrin	50.0	0.008
Pyrinex 48 EC	Chlorpyrifos	480.0	0.480

**Table S2.** Toxicological and ecotoxicological characteristics of the active ingredients based on PPDB

Active ingredient	LD <sub>50</sub> honeybees (µg a.i. bee <sup>-1</sup> )	LC <sub>50</sub> earthworms (mg a.i. kg <sup>-1</sup> soil)	LC <sub>50</sub> fish (mg L <sup>-1</sup> )	EC <sub>50</sub> daphnia (mg L <sup>-1</sup> )	NOEC algae (mg L <sup>-1</sup> )	AOEL (mg kg <sup>-1</sup> bw day <sup>-1</sup> )
Pyraclostrobin	100	567	0.006	0.016	–	0.015
Fluxapyroxad	100	1000	0.466	6.76	–	0.040
Epoxiconazole	85	500	0.92	3.13	0.0078	0.008
Pinoxaden	100	500	10.3	52.0	–	0.100
2,4-D	90	350	100	134.2	100	0.020
Clethodim	199.3	27	25	–	–	0.200
Paraquat	9.26	1000	19	4.4	–	0.0004
Chlorantraniliprole	4	1000	1.09	0.0116	–	0.360
Lambda-cyhalothrin	0.038	500	0.0021	0.00023	0.31	0.00063
Chlorpyrifos	0.068	129	0.025	0.0001	0.043	0.010

Source. Pesticide Properties Database (PPDB) (Agriculture & Environment Research Unit, n.d.).